TOPFARM. Background, vision - and challenges

Larsen, Gunner Chr.; Aagaard Madsen, Helge; Larsen, Torben J.; Mann, Jakob; Bingöl, Ferhat

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TOPFARM – background, vision … and challenges

Gunner C. Larsen,

Helge Aa. Madsen,

Torben J. Larsen,

Jakob Mann,

Ferhat Bingöl, …

Outline

- Introduction
- Observations
- DWM model
- Vision/strategy
- Challenges
- Conclusion
- Announcement

Introduction (1)

- TOPFARM acronym for: NEXT GENERATION DESIGN TOOL FOR OPTIMISATION OF WIND FARM TOPOLOGY AND OPERATION
- EU project
- The TOPFARM project addresses optimisation of wind farm topology and control strategy based on aeroelastic modelling of loads as well as of power production

Introduction (2)

- Partners
  - Risø-DTU (coordinator)
  - MEK-DTU
  - Cambridge Environmental Research Consultants ltd.
  - DONG ENERGY
  - Garrad Hassan and Partners ltd.
  - Teknikgruppen
  - Universidad Politécnica de Madrid
  - Germanischer Lloyd Industrial Services GmbH
  - Vestas Wind Systems A/S

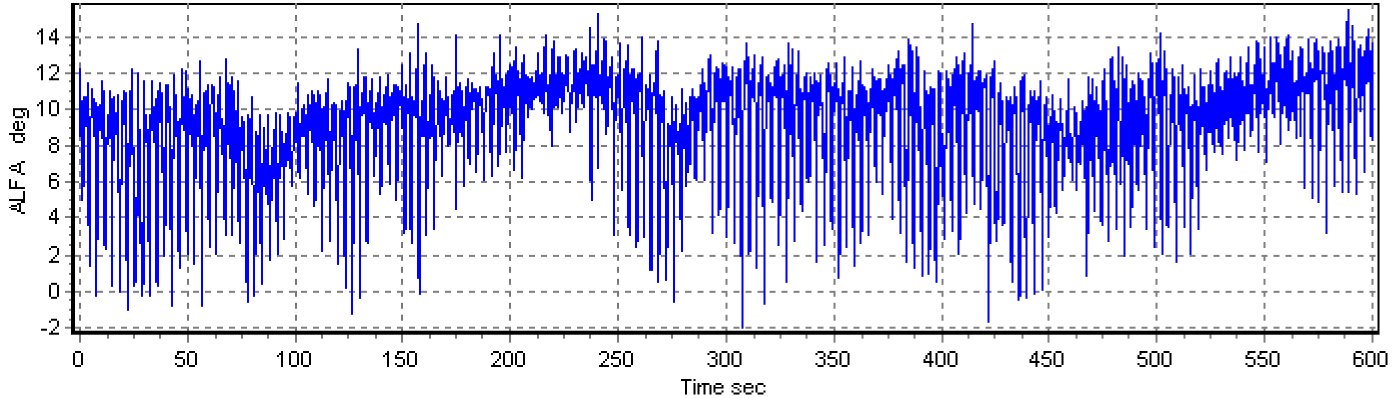
Observations (1)

- Full scale experiment in 2003 on an 80 m, 2 MW NEG-MICON turbine in Tjæreborg

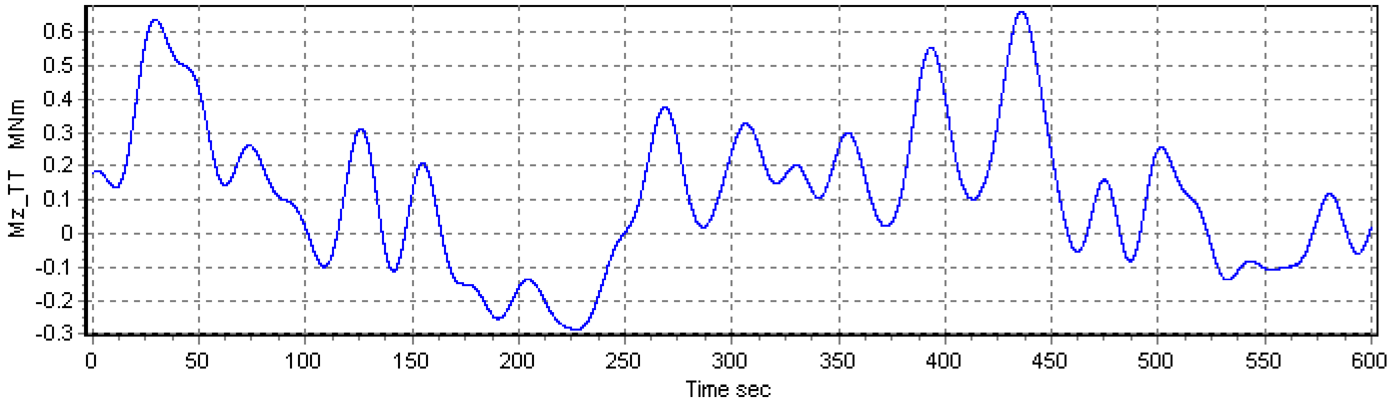
Observations (2)

- Increased yaw moments in partial wake situations as caused by a meandering wake deficit

LOCAL INFLOW ANGLE



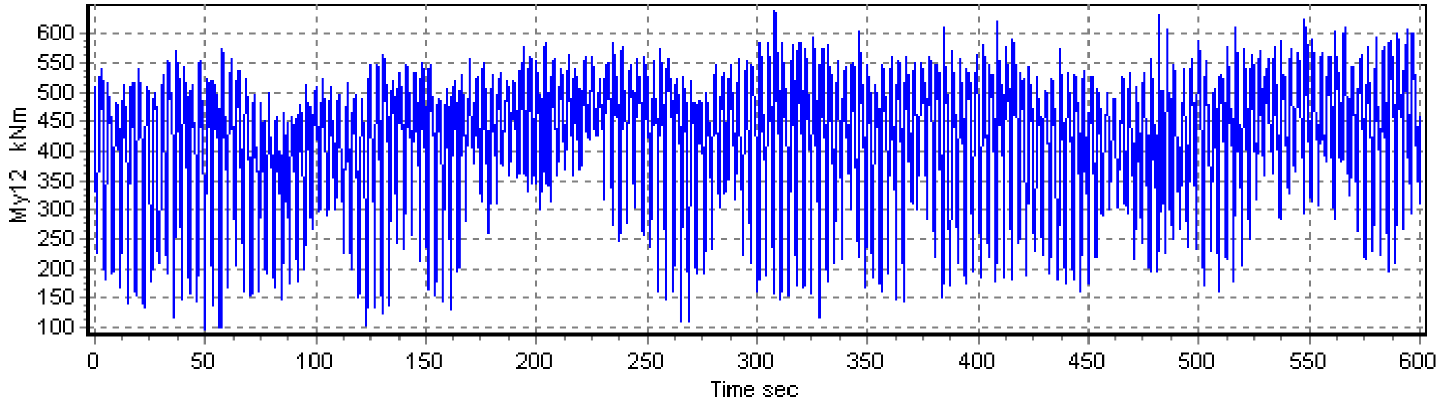
FILTERED YAW MOMENT



Observations (3)

- Intermittent character of a fatigue generating flapwise load pattern as caused by a meandering wake deficit

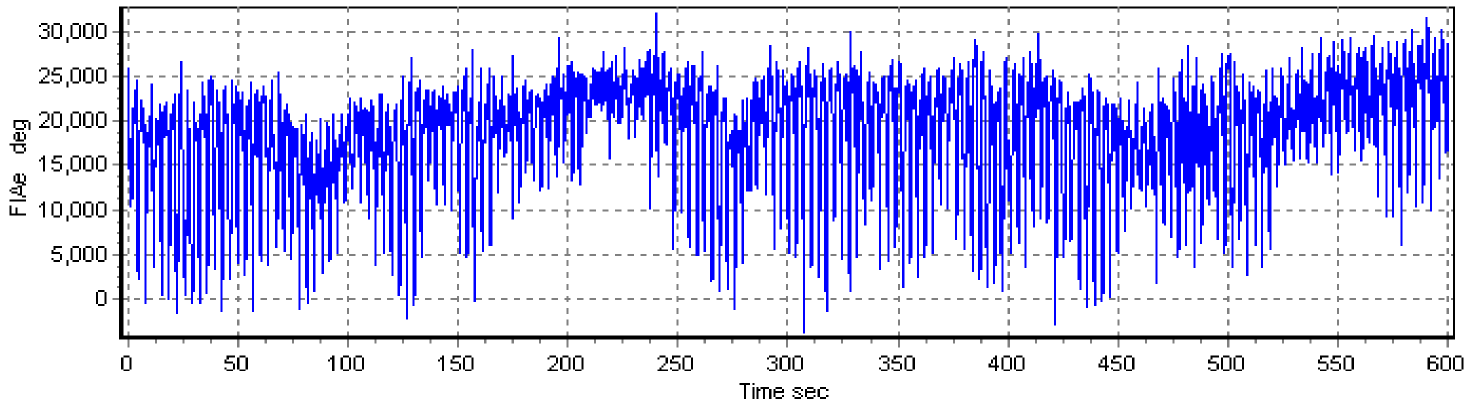
FLAPWISE MOMENT



Derived load signal from measured "alfa" and local relative velocity.

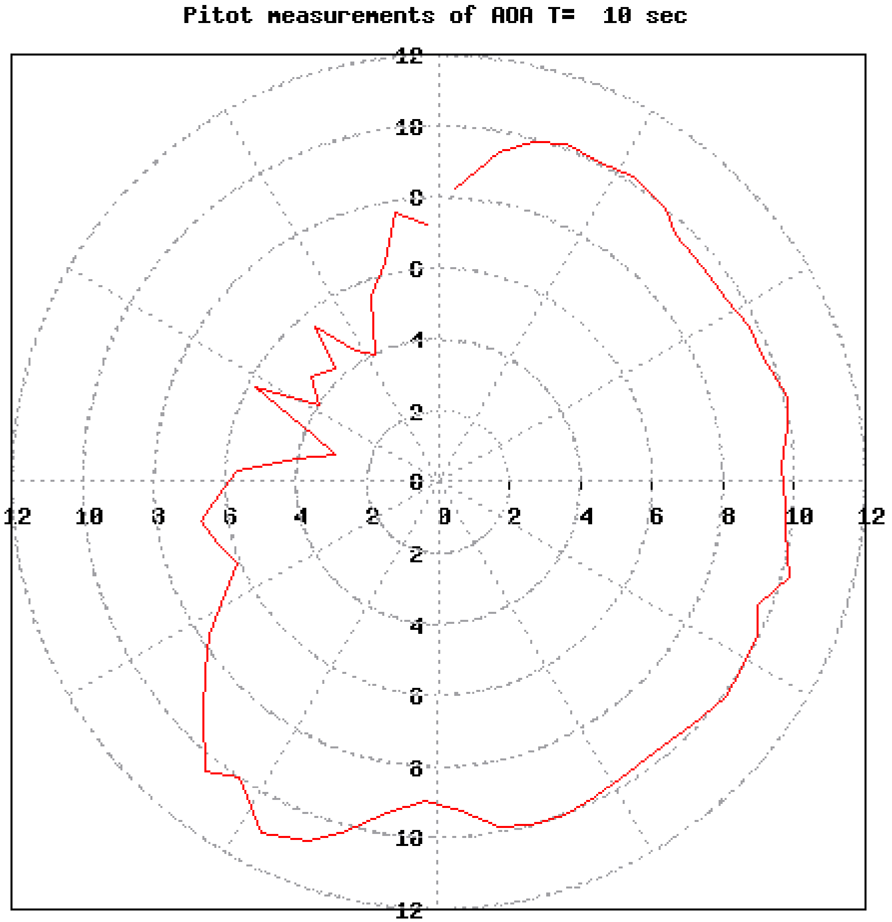
Uncalibrated

$$F_{aero} \approx W^2 (2\pi\alpha)$$



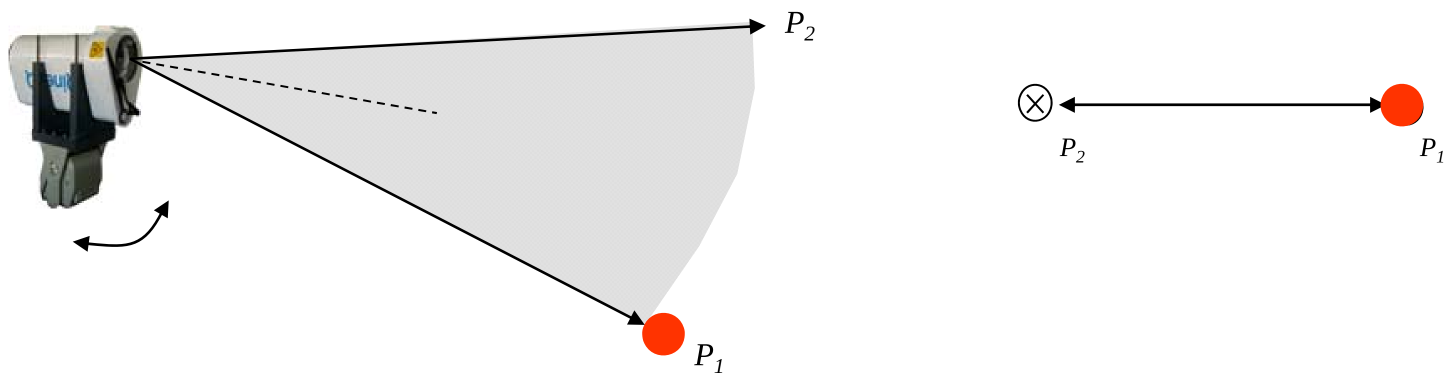
Observations (4)

- Wake deficit dynamics illustrated by measured AOA



Observations (5)

Observations (6)

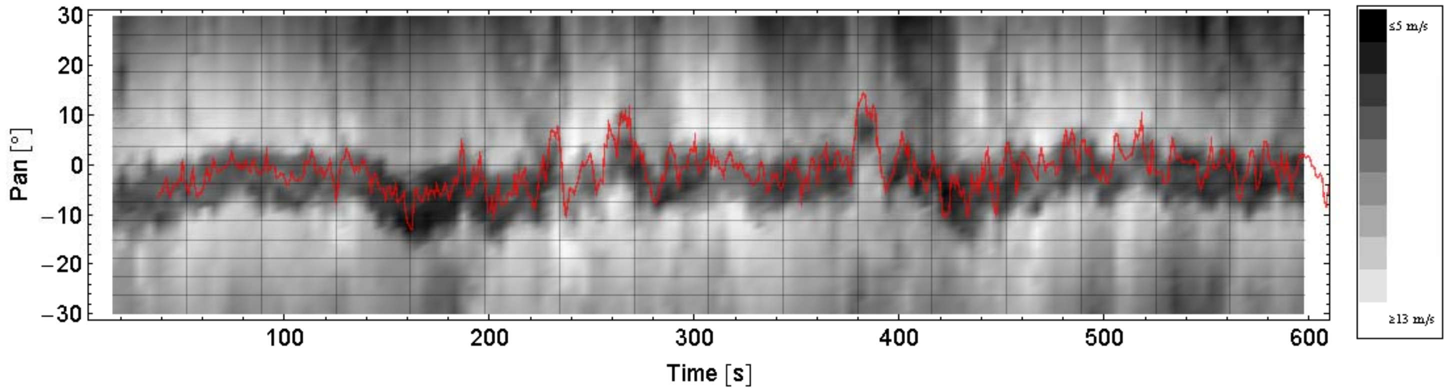


- 1D scanning mode
  - Derived from “Staring Mode” and the movement of the Head in pan direction;
  - Captures data from points on an arc (136Hz).

Observations (7)

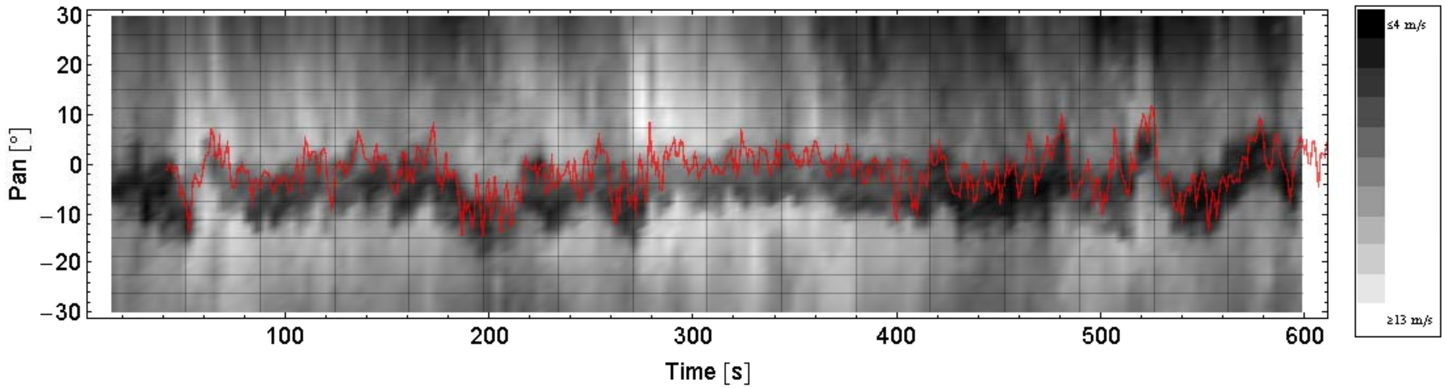
Date 2005–11–15 Time 18:00 Number of Scans 82274

LiDAR				Turbine				Met.Mast							
WS [m/s]				Yaw [°]				WS [m/s]				WD [°]			
Mean	Min	Max	StdDev	Mean	Min	Max	StdDev	Mean	Min	Max	StdDev	Mean	Min	Max	StdDev
9.54	4.59	14.50	1.59	294.0	283.0	310.0	4.1	11.30	7.66	13.90	1.22	295.0	295.0	296.0	0.1



Date 2005–11–15 Time 18:20 Number of Scans 82300

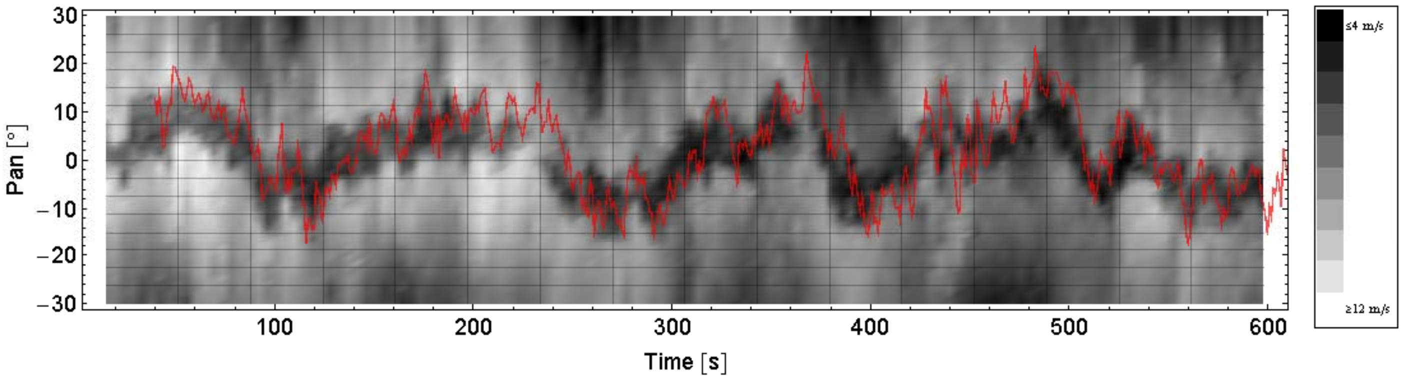
LiDAR				Turbine				Met.Mast							
WS [m/s]				Yaw [°]				WS [m/s]				WD [°]			
Mean	Min	Max	StdDev	Mean	Min	Max	StdDev	Mean	Min	Max	StdDev	Mean	Min	Max	StdDev
8.64	3.74	14.60	1.67	293.0	275.0	307.0	4.7	10.10	6.88	13.70	1.29	294.0	285.0	296.0	3.2



Observations (8)

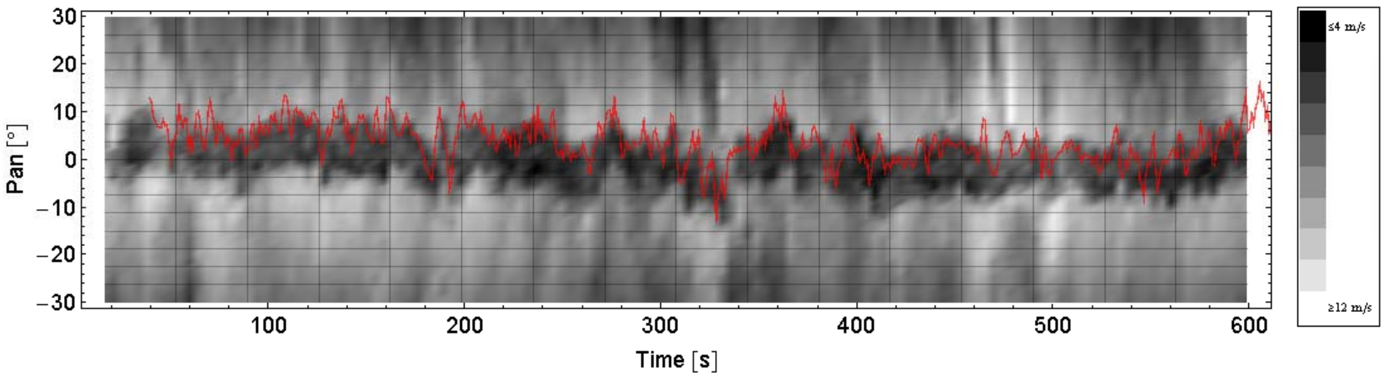
Date 2005–11–15 Time 21:20 Number of Scans 78501

LiDAR				Turbine				Met.Mast							
WS [m/s]				Yaw [°]				WS [m/s]				WD [°]			
Mean	Min	Max	StdDev	Mean	Min	Max	StdDev	Mean	Min	Max	StdDev	Mean	Min	Max	StdDev
7.76	3.07	13.10	1.56	279.0	258.0	296.0	5.6	8.74	5.43	12.40	1.37	277.0	265.0	289.0	6.0



Date 2005–11–15 Time 19:00 Number of Scans 81992

LiDAR				Turbine				Met.Mast							
WS [m/s]				Yaw [°]				WS [m/s]				WD [°]			
Mean	Min	Max	StdDev	Mean	Min	Max	StdDev	Mean	Min	Max	StdDev	Mean	Min	Max	StdDev
8.39	3.58	13.20	1.33	290.0	273.0	302.0	4.3	9.96	7.56	12.60	0.90	286.0	286.0	286.0	0.0

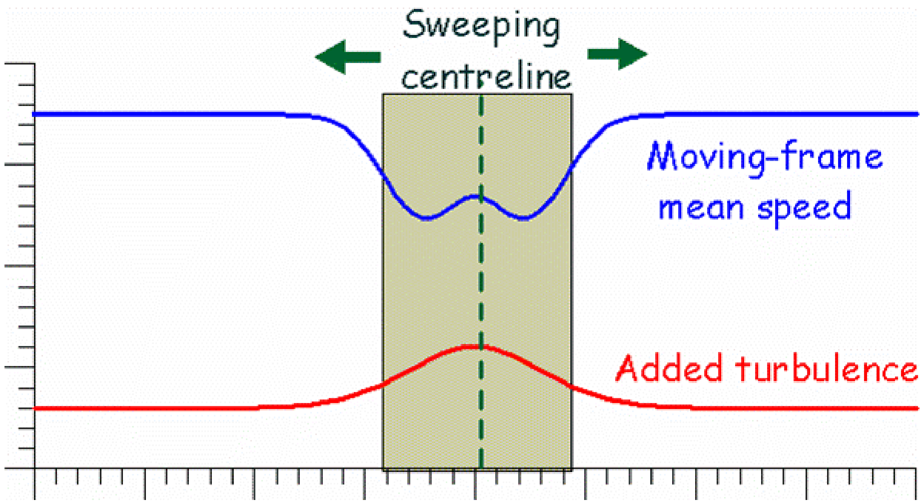


DWM model (1)

- The goal was to formulate consistent model that is
  - based on physical first principles … and thus e.g. includes a description of the modified *structure* of the apparent intermittent turbulence as seen by downstream turbines
  - presents a *unifying* description of wake consequences in the sense that both *production* and *load* aspects can be dealt with … which in turn opens for optimization of e.g. control and topology of wind farms
  - easy to apply with state-of-the-art aeroelastic codes

DWM model (2)

- DWM philosophy
  - The core of the model is a *split in scales* in the wake flow field, with large scales being responsible for stochastic *wake meandering*, and small scales being responsible for wake *attenuation* and *expansion* in the meandering frame of reference as caused by turbulent mixing

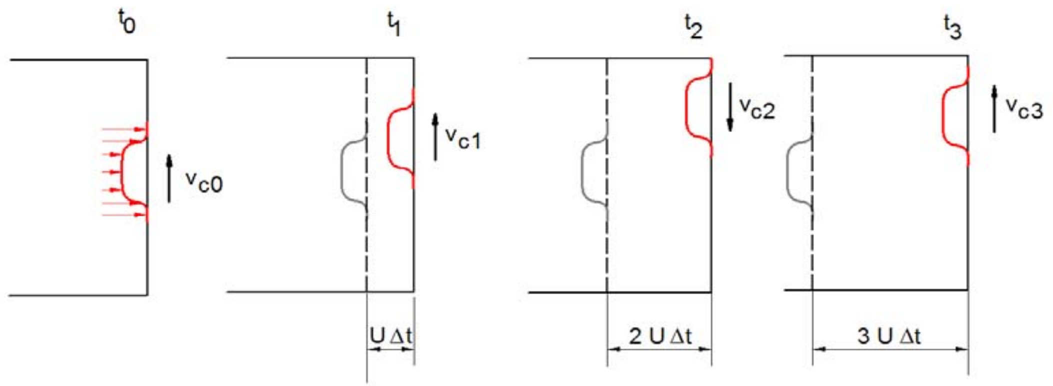


DWM model (3)

- DWM *main ingredients*
  1) The *quasi-steady wake deficit* is the wake deficit formulated in the moving (meandering) frame of reference. It includes *wake expansion and attenuation* (caused by turbulent mixing as well as by the rotor pressure field) as function of downstream position. Generation based on BEM and thin layer NS approximation (i.e. BLE)
  2) *Added wake turbulence* includes contributions from mechanically generated turbulence (wake shear), as well as from the blade bound vorticity. *Inhomogeneous* - vary in general across the wake regime and with down stream distance

DWM model (4)

- The DWM *main ingredients* (cont.):
  3) *Wake* down-stream transportation (meandering):
     - *Longitudinal transportation* (i.e. transportation in the mean wind direction): Taylor advection
     - *In plane (transversal/vertical) transportation:* A 3D turbulence wind field is generated that, after suitable low-pass filtering, is used as “transport media” for the wake in-plane propagation



DWM model (5)

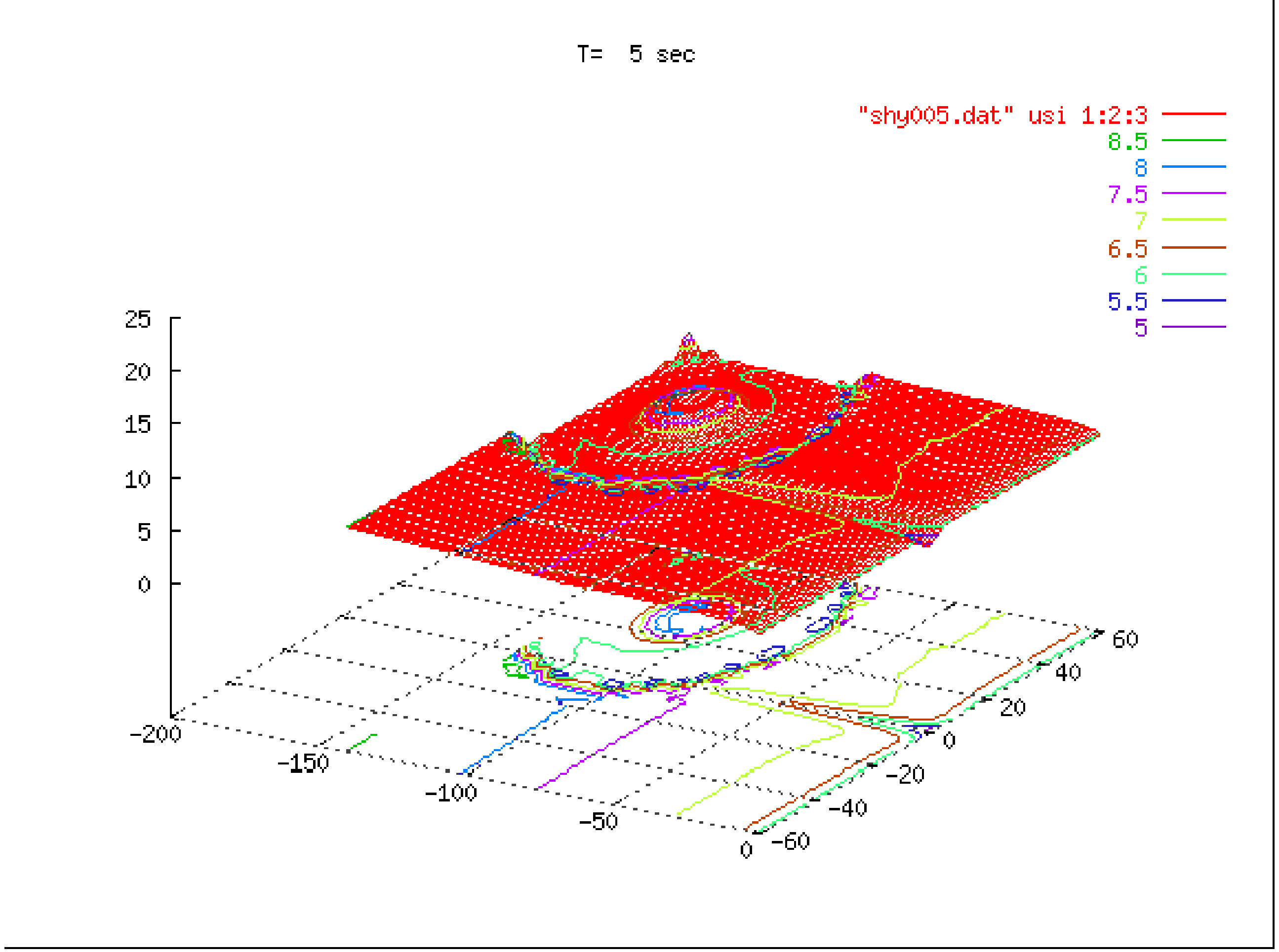
- The DWM *main ingredients* (cont.):

  4) A sequence of *"deficit-releases"* is considered

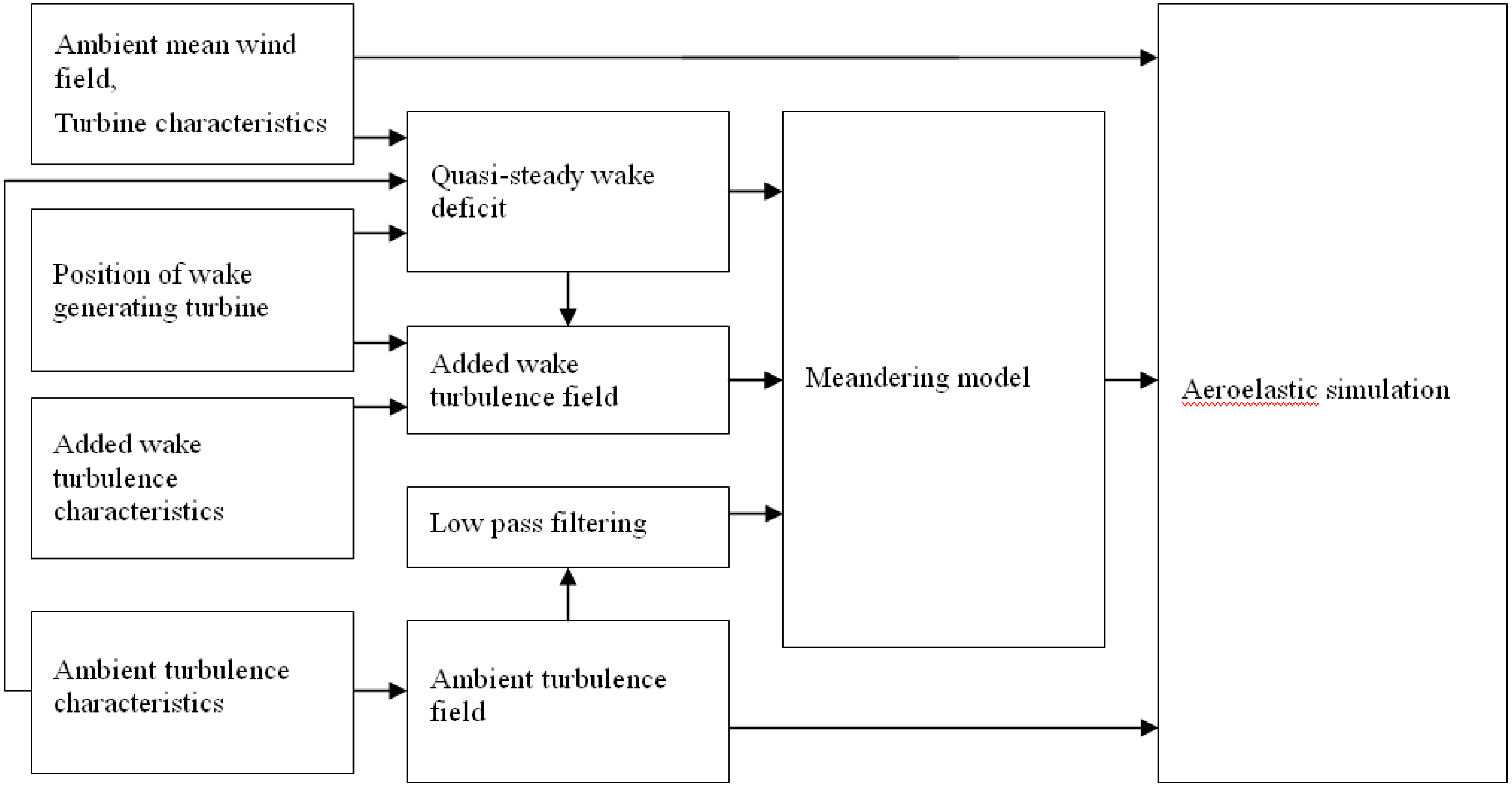
     - Each *deficit* is modelled according to the (U+u) wind speed at the instant of release by interpolation in a "deficit table"

DWM model (6)

- Example – stochastic wake displacement at a given downstream position



DWM model (7)



Ambient mean wind field,
Turbine characteristics
Quasi-steady wake deficit
Position of wake generating turbine
Added wake turbulence field
Added wake turbulence characteristics
Low pass filtering
Meandering model
Aeroelastic simulation
Ambient turbulence characteristics
Ambient turbulence field

Vision/strategy (1)

1) Penalty function

$$\Pi(\mathbf{x},\mathbf{y},C_{turb},C_{farm}) = P(\mathbf{x},\mathbf{y},C_{turb},C_{farm}) - D(\mathbf{x},\mathbf{y},C_{turb},C_{farm}) - FC(\mathbf{x},\mathbf{y}) - MC(\mathbf{x},\mathbf{y},C_{turb},C_{farm})$$

P(*): Production revenue ;

D(*): Fatigue driven degradation costs ;

FC(*) : Financial costs ;

MC(*) : Maintenance costs

$\mathbf{x} = (x_{turb\ 1}, x_{turb\ 2}, \ldots, x_{turb\ N})$

$\mathbf{y} = (y_{turb\ 1}, y_{turb\ 2}, \ldots, y_{turb\ N})$

Vision/strategy (2)

2) Seek stationary points

$$\begin{aligned}\delta\Pi(\mathbf{x},\mathbf{y},C_{turb},C_{farm}) &= \delta_x \Pi(\mathbf{x},\mathbf{y},C_{turb},C_{farm})\delta\mathbf{x} + \delta_y \Pi(\mathbf{x},\mathbf{y},C_{turb},C_{farm})\delta\mathbf{y} \\ &\quad + \delta_{Ct} \Pi(\mathbf{x},\mathbf{y},C_{turb},C_{farm})\delta C_{turb} + \delta_{Cf} \Pi(\mathbf{x},\mathbf{y},C_{turb},C_{farm})\delta C_{farm} \\ &= 0\end{aligned}$$

under the constraints

$$\forall i : (x_{turb\ i}, y_{turb\ i}) \in A$$

$$\forall i, j : (x_{turb\ i} - x_{turb\ j})^2 + (y_{turb\ i} - y_{turb\ j})^2 \geq dist_{min}^2$$

Vision/strategy (3)

3) Identify global optimum

$$GM = \max_{j} \Pi\left(\mathbf{x}_j, \mathbf{y}_j, C_{turb\,j}, C_{farm\,j}\right)$$

with

$$\left(\mathbf{x}_j, \mathbf{y}_j, C_{turb\,j}, C_{farm\,j}\right)$$

being stationary points for the penalty function

Vision/strategy (4)

4) Reduction of computational effort - structured grid

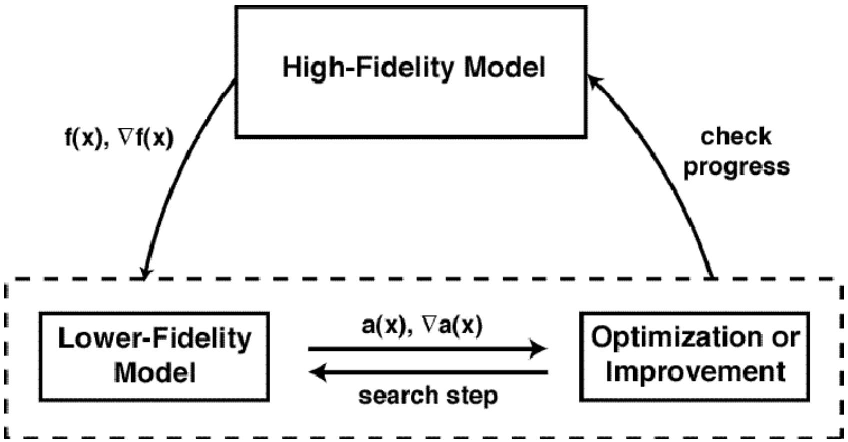
$$f\left(\mathbf{x},\mathbf{y};\mathbf{parameters}\right)=0$$

and thereby

$$\delta\mathbf{x}\,,\delta\mathbf{y}\longrightarrow\delta\mathbf{parameters}$$

Vision/strategy (5)

5) Reduction of computational effort – multi (variable) fidelity approach



i.e. $\Pi \longrightarrow \left(\Pi_{simple}, \Pi_{medium}, \Pi_{advanced}\right)$ **describing the *same* physics**

Vision/strategy (6)

Examples on possible Π's

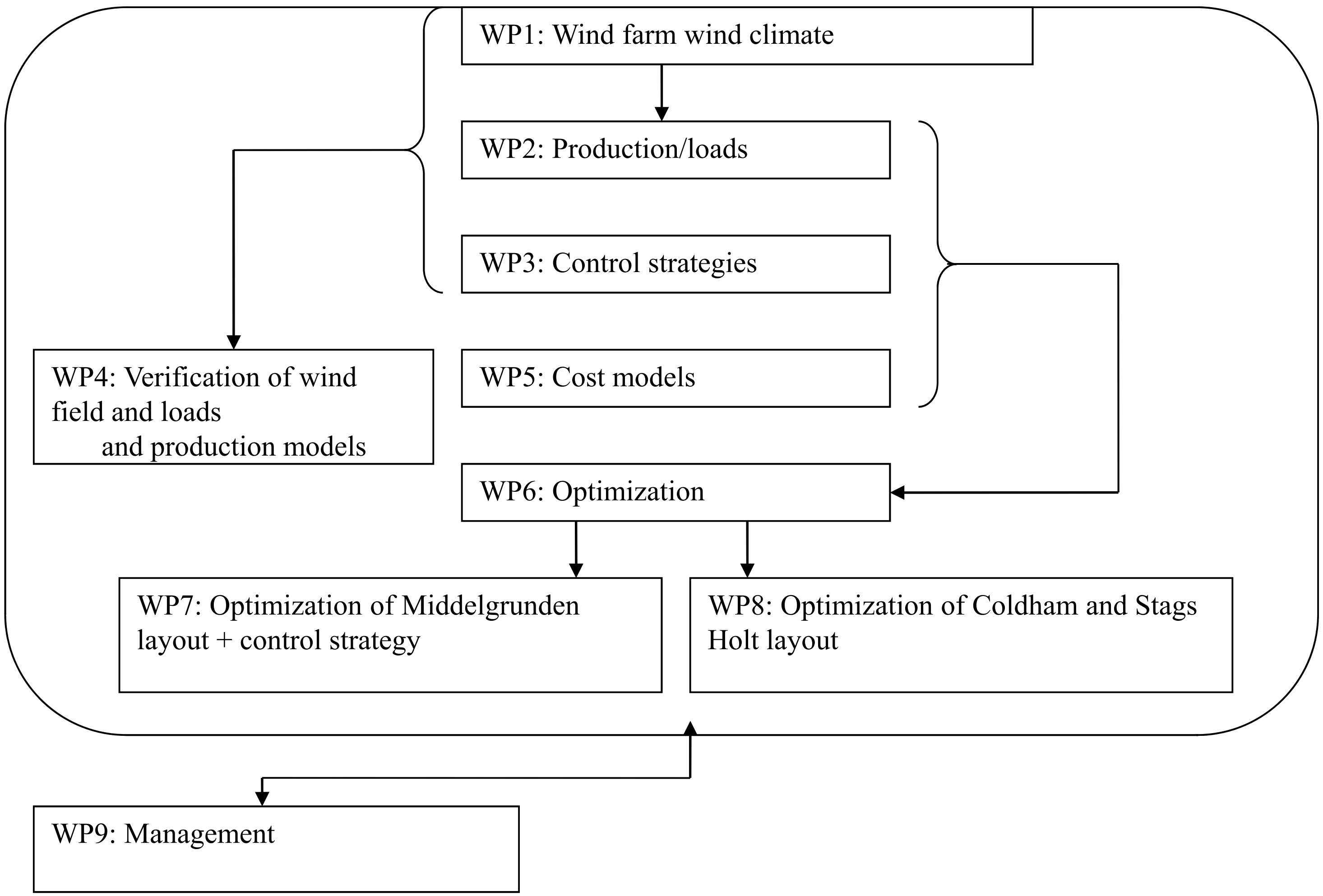
1) Π_{simple} : existing simple crude optimization model, however, possibly refined with a bit more complex (analytical) wake modelling and supplemented with a simple load estimation
2) Π_{medium} : optimization based on table look up and interpolation in data, which is generated prior to the optimization for a limited number of general load cases (based on the complex model)
3) $\Pi_{advanced}$: referring to model level of highest complexity characterized by full aeroelastic load calculations combined with wake meandering, etc.

Vision/strategy (7)

The basic elements in the penalty function links to different WP's in the TOPFARM project

- $P(\mathbf{x},\mathbf{y},C_{turb}, C_{farm})$: **WP1, WP2, WP3**
- $D(\mathbf{x},\mathbf{y},C_{turb}, C_{farm})$: **WP1, WP2, WP3**
- $FC(\mathbf{x},\mathbf{y},C_{turb}, C_{farm})$: **WP5**
- $MC(\mathbf{x},\mathbf{y},C_{turb}, C_{farm})$: **WP5**
- ($\delta\Pi$: **WP6**)

Vision/strategy (8)



Challenges

Consideration on the overall goal:

A a major challenge for the project is to develop fast approximate models and yet preserve the essential physics of the problem. This may be illustrated by a simple example: Consider the optimization of a wind farm consisting of 100 wind turbines, where the optimization involves 72 wind directions (5 degree bins), 20 mean wind speeds (1 m/s bins), 500 iterations in the numerical optimization scheme, and real time 10-minute aeroelastic computations. Discharging the computational effort needed to simulate the internal wind farm wind climate (that has to be updated for each iteration in the optimization loop) the requested computational time is 500.000 days and nights (for one processor). This challenge inevitable has to be meet on all levels ranging from the wind farm wind field simulation over the aeroelastic simulation to the optimization

Conclusion(s)

- We have developed a new design philosophy (i.e. the DWM model complex) for wind turbines in wake conditions based on physical first principles
- For *solitary* wakes, we have successfully verified the model performance against full scale LiDAR- and pitot tube based measurements allowing for instantaneous resolution of the wake (and thus the position)
- The new design philosophy is a corner stone in the EU TOPFARM project dealing with wind farm optimization
- Work on wake interaction and added wake turbulence (i.e. mechanically generated turbulence originating from the wake shear field as well as from the break down of organized flow structures such as tip- and root vortices) is in progress

Announcement

- A EUROMECH colloquium will be organized 20–22 October 2009 in Madrid within the framework of TOPFARM. The theme for EUROMECH colloquium 508 is “Wind Turbine Wakes”

WP1

- WP1 deals with modelling and simulation of the complex flow field inside a wind farm

“This includes modelling of the wake meandering phenomenon as well as the associated intermittent turbulence characteristics. The meandering process will relate to the rotor aerodynamics, the wind turbine control strategy and the terrain influence on the ambient large scale turbulence. The development of a meandering wake model (Task 1.1) and associated turbulence simulation tool (Task 1.2) runs in parallel. The work with interface modules (Task 1.3) provides output in the formats needed for the wind turbine load estimation modelling performed in WP 2. The simulation software will be operational in month 15, followed by a verification and calibration phase (Task 1.4) using input from WP4”

WP2

- WP2 deals with full aeroelastic load- and production modelling of the individual wind turbines constituting the wind farm

"…based on the detailed three dimensional dynamic wake wind field modelling resulting from WP1. WP2 needs input from WP1. Task 2.1 applies detailed simulations, whereas Task 2.2 applies stochastic input. These tasks run in parallel and are followed by a model comparison (Task 2.3). The load simulation tools and power production estimates will be available in month 18 and comparison of the methods stops in month 24 before the test cases (WP7, WP8)"

WP3

- WP3 deals with control strategies and will address total wind farm power output as well as fatigue life consumption for individual turbines

"Suitable control algorithms and control options will be developed in order to facilitate an efficient and successful wind farm optimisation study. Different levels of control strategies will be modelled and examined in this work package (Tasks 3.1, 3.2, and 3.3) and will be available in month 18. The selection of control strategies ranges from control strategies aiming at reducing the loads on the individual wind turbine to downstream de-rating used as a wind farm control strategy option. The evaluation of these (Task 3.4) is completed in month 24"

WP4

- WP4 deals with verification of the developed sub models in WP's 1-3 using dedicated full-scale measurements

"The measurements will, among other things, encompass detailed wake field recordings obtained from advanced sensoring techniques using rotating five-hole pitot tubes and a Laser Doppler anemometer. The measuring campaign is initiated by a planning phase and followed by data analysis and verification phase. Results will be available before initiation of the demonstration case (WP7)"

WP5

- WP5 deals with models of relevant capital costs and operation and maintenance costs

"… primarily linking these costs to the turbine fatigue lifetime consumption. It needs little input from other work packages and will be completed in month 18"

WP6

- WP6 deals with development of an optimisation tool using the sub-models developed and verified in work packages WP1-WP5

"… allowing optimisation of a wind farm layout considering energy production, aeroelastic loads and total installation costs. Must allow for area constraints (e.g. extend of shallow water regime). The optimisation tools are ready in month 18"

WP7

- WP7 is a demonstration example.

“It demonstrates the potential of the developed optimisation method in design of *new* wind farms. This is achieved by re-designing the 40MW Middelgrunden offshore wind farm”

WP8

- WP8 is also a demonstration example.

"It demonstrates the potential of the developed optimisation package in design of a *new* wind farm. This is achieved by re-designing the Coldham onshore site, consisting of 8 Vestas V80 turbines, and the Stags Holt onshore site, consisting of 9 Vestas V90 turbines"